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Mesozoic subsidence and stretching models of the lithosphere in Switzerland (Jura, Swiss Plateau and Helvetic realm)

By BERNARD LOUP [1])

Key words: subsidence analysis, backstripping, uniform stretching, non-uniform discontinuous stretching, intracratonic basins, Mesozoic, Jura, Plateau, Helvetic realm.

ABSTRACT

The tectonic subsidence is reconstructed for 57 sections covering the Mesozoic record of the Jura, Swiss Plateau and Helvetic realm. The following corrections have been made: compaction, tectonic deformation, erosion, minimum and maximum bathymetry, long term eustatic sea-level fluctuations. An Airy-type response of the basement to overburden has been assumed for the backstripping. Possible basin-forming mechanisms are investigated by comparing the reconstructed tectonic subsidence to three models of lithospheric stretching (uniform, crustal and subcrustal extension). The theoretical curves have been computed with finite rifting, standard physical parameters for the lithosphere and Airy compensation without lateral heat loss.

The tectonic subsidence obtained is polyphase and cannot be described by a single event. Several short term phases (called here '2nd order phases'), with a mean duration of 50 to 60 M.y., are superimposed on the long term Mesozoic subsidence ('1st order', duration longer than 100 to 150 M.y.). The highest tectonic subsidence rates are encountered during the late Early to Late Triassic in the Jura and Plateau, during the Late Jurassic on the External massifs, during the late Early Jurassic and the early Middle Jurassic in the Morcles-Doldenhorn area, and during the Early Cretaceous in the Wildhorn and South-Helvetic domains. Each paleogeographic realm is composed of several tectonic subsidence patterns: the number, timing, duration and shape of the different phases vary significantly from one profile to another. However, subsidence is relatively uniform within each Helvetic paleogeographic sub-domain.

The 1st order Mesozoic subsidence is often difficult to model, and adequate correlations are not realistic (too long rifting periods). It is proposed that Mesozoic subsidence resulted from several successive rifting events. The 2nd order tectonic subsidence phases are more easily modelled. Relatively low stretching factors are obtained: 3 to 15% for the crust and 0 to 25% for the lithospheric mantle. Two or three models are necessary to reproduce the tectonic subsidence in each paleogeographic realm. An unique extension process can however explain the burial history recorded within each Helvetic sub-domain: uniform stretching model fits the Aiguilles Rouges and Aar external massifs, subcrustal extension model fits the Morcles-Doldenhorn and Raron syncline realms, and crustal to uniform extension models fit the Wildhorn and South-Helvetic zones. These various and contrasting extension modes are possibly linked by oblique detachments through the lithosphere.

RÉSUMÉ

L'analyse de la subsidence tectonique porte sur les séries mésozoïques de 57 profils du Jura, du Plateau suisse et du domaine helvétique. Les corrections suivantes ont été effectuées: compaction, déformation tectonique, érosion, bathymétries minimale et maximale, variations eustatiques à long terme. Une réponse à la sur-

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charge de type Airy a été retenue pour le 'backstripping'. La comparaison de la subsidence tectonique obtenue avec trois modèles théoriques d'extension lithosphérique permet d'étudier les mécanismes pouvant être à l'origine des bassins considérés. Les courbes théoriques ont été établies avec un rifting de durée 'finie', des paramètres lithosphériques standard et une compensation de type Airy sans flux thermique latéral.

La subsidence tectonique obtenue est de nature polyphasée et ne peut pas être décrite par un événement unique. Plusieurs phases de court terme (de '2ème ordre'), dont la durée moyenne se situe entre 50 et 60 M.a., sont superposées à la subsidence mésozoïque à long terme ('1er ordre'), d'une durée supérieure à 100–150 M.a. Les taux de subsidence les plus élevés sont enregistrés entre le sommet du Trias inférieur et le Trias supérieur dans le Jura et le Plateau, au Malm au toit des massifs cristallins externes, entre le Lias supérieur et le Dogger inférieur dans le domaine Morcles-Doldenhorn, et au Crétacé inférieur dans les domaines Wildhorn et Sudhelvétique. Chaque domaine paléogéographique est constitué de plusieurs modes de subsidence: le nombre, la durée, la forme et l'époque des différentes phases peuvent varier de façon significative d'un profil à l'autre. La subsidence est cependant relativement homogène dans chaque sous-domaine de l'Helvétique.

La modélisation de la subsidence de 1er ordre est souvent difficile. De plus, en raison de durées d'extension trop longues, les quelques corrélations apparemment possibles ne sont pas plausibles. La subsidence mésozoïque doit être considérée comme le produit de plusieurs périodes distensives. Les phases de 2ème ordre se laissent mieux caractériser. Les taux d'extension sont relativement bas: de 3 à 15% dans la croûte et de 0 à 25% dans la lithosphère sous-crustale. Pour chaque domaine paléogéographique, deux à trois modèles sont nécessaires pour générer la subsidence tectonique observée. Un mécanisme unique peut néanmoins être à l'origine de l'enfouissement dans chaque sous-domaine helvétique: extension homogène pour les massifs des Aiguilles Rouges et de l'Aar, extension sous-crustale pour les domaines Morcles-Doldenhorn et le synclinal de Raron, extension crustale pour les régions en position sud-helvétique. Ces modes d'extension variables sont peut-être reliés par des détachements intra-lithosphériques obliques.

1. Introduction

In the external part of the Alps and Alpine foreland, orogenic events have overprinted the lithospheric structure and the geometry of the former Mesozoic sedimentary basins. In such a context, subsidence analysis represents a tool to investigate the basin history and to interpret the possible basin-forming mechanisms.

Two types of subsidence are classically distinguished:

- *the total subsidence*, where the burial history of a marker-bed or specific interface through time is corrected for compaction, depositional water depth and eustatic sea-level changes;
- *the tectonic subsidence*, where the effects of sediment loading are removed ("backstripping"; [tectonic subsidence] = [total subsidence] – [subsidence due to sediment load]).

In the Alps, the total subsidence has been frequently discussed (e.g. Lemcke 1974, Homewood et al. 1986: Swiss Plateau; Homewood & Lateltin 1988: Swiss Plateau and North-Helvetic realm; Wildi et al. 1989: Jura, Plateau and Helvetic realm; Funk 1985: Glarus Alps; Mettraux 1989, Dupasquier 1990: "Préalpes médianes"; Arnaud 1988: part of the Subalpine chains). By contrast, only few studies report also on tectonic subsidence (e.g. Winterer & Bosellini 1981, Bertotti 1991: Southern Alps; Rudkiewicz 1988: Grenoble-Briançon transect; Loup 1992a, b: Jura, Plateau and Helvetic realm).

In this study, the technique of subsidence analysis is applied to 57 stratigraphic sections from the Jura, Swiss Plateau and Helvetic paleogeographic domains. The investigated area covers more precisely the southern part of the Tabular Jura, the

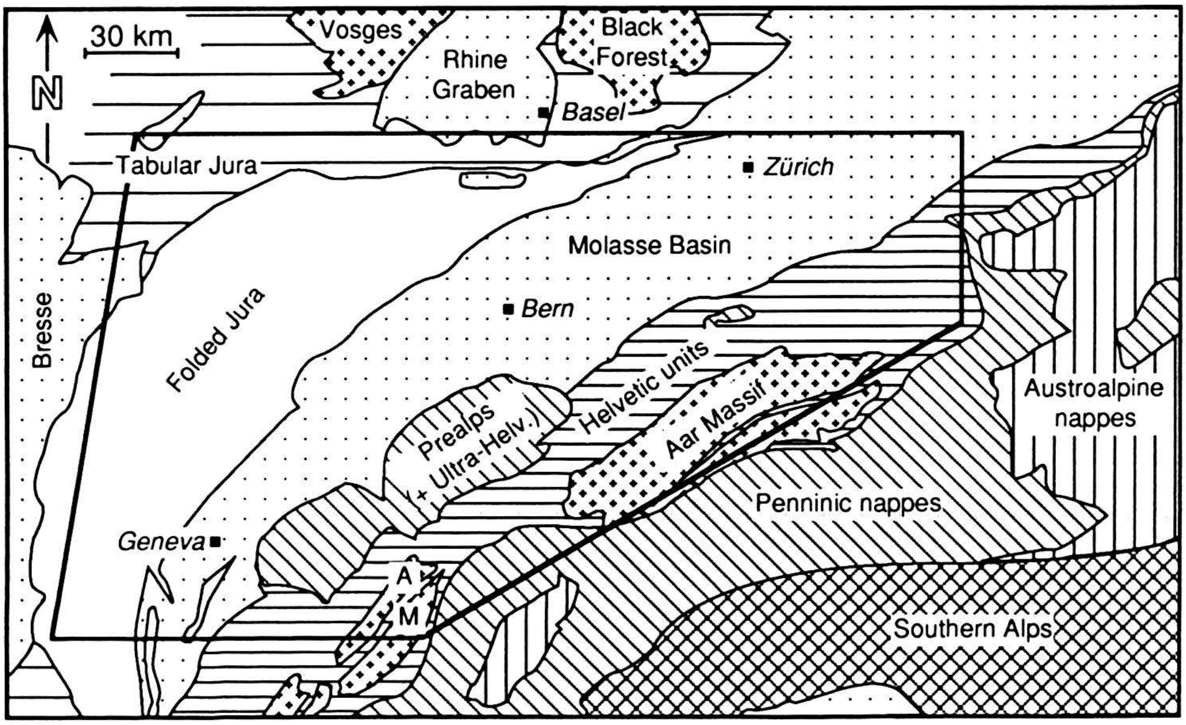

Fig. 1. Simplified structural map of the Alps, Swiss Plateau and Jura, with outline of the study area. Dotted: main Tertiary basins; with crosses: crystalline basement massifs of the European Foreland and Helvetic units (A: Aiguilles Rouges, M: Mont Blanc).

Folded Jura belt, the Swiss Plateau and the Helvetic units between the Aravis massif and the Helvetic nappes of eastern Switzerland (Fig. 1). Some profiles already discussed by Funk (1985) and Wildi et al. (1989) have been recalculated and complemented with tectonic subsidence analysis. This set of sections has been augmented with new profiles from the Helvetic realm of western Switzerland. Attention has been restricted to the Mesozoic subsidence history and basin-forming mechanisms. The Tertiary inversion of the study area and foreland basin formation are beyond the scope of this paper (see for example Homewood et al. 1986, Allen et al. 1991). After a brief discussion of the parameters and methods used here, a first purpose of this contribution is to reconstruct the tectonic subsidence history and to discuss its distribution in space and time over the study area. The monophase or polyphase character of the obtained subsidence is also investigated.

The basin-forming or subsidence-driving mechanisms can be investigated by comparing tectonic subsidence curves with curves derived from theoretical models of basin formation and evolution. Three processes of lithospheric extension have been considered here: uniform (McKenzie 1978), crustal and subcrustal stretching (e.g. Hellinger & Sclater 1983). The main advantage of these models is to differentiate more thermal from more fault-controlled processes during basin formation. A second aim is thus to discuss the possible subsidence-driving mechanisms within each paleogeographic domain of the study area.

This contribution is part of the Eclogae Special Volume on the Molasse Basin because some of the presented profiles are concerned with the Mesozoic series underlying the Molasse Basin. The subsidence in an area strongly depends on the basin-forming mechanisms in surrounding regions; it is therefore of prime interest to investigate the Jura and Helvetic realms in order to understand the burial history of the Molasse Basin.

2. Method of subsidence analysis

Following early burial history curves by Gürich (1896, in von Bubnoff 1931) for Poland and by Lemoine (1911) for the Paris Basin, the technique of subsidence analysis as used today has been described by Sleep (1971), Watts & Ryan (1976), Steckler & Watts (1978) and Van Hinte (1978). Numerous later papers have applied this method or emphasized specific aspects of the technique. Its applicability to tectonized Alpine situations such as the Glarus region and the European Mesozoic marginal platform has been discussed by Funk (1985), Wildi et al. (1989) and Loup (1992a, b). Basically the same approach has been applied here (Fig. 2). Introduced corrections are briefly discussed in the following sections, with additional comments on sediment dating, stratigraphic section reconstruction and backstripping technique.

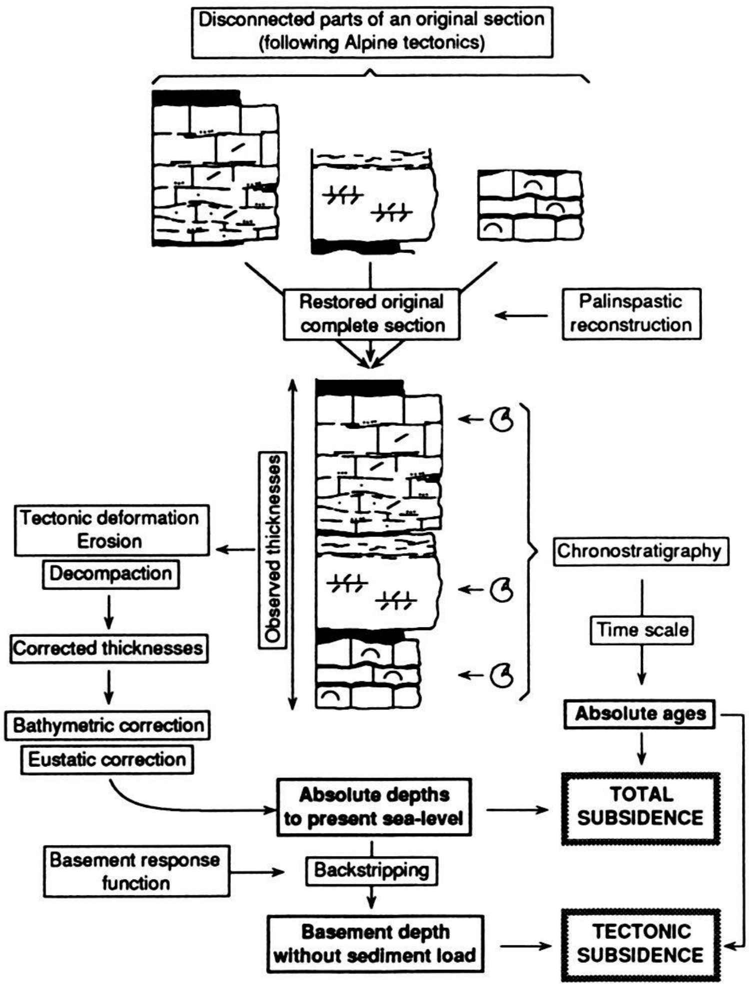

Fig. 2. Subsidence analysis: synthetic view of the method. See text for a brief discussion of the different steps. See also Fig. 3.

2.1 Reconstruction of the original sedimentary pile

In the Jura mountain belt and in the Plateau, complete stratigraphic sections can be directly established from outcrop or borehole data. Although tectonic displacement is locally significant, the original sedimentary pile has not been dramatically disrupted. By contrast, the original sequence of lithologic units in the Helvetic *sensu lato* [2]) has been strongly dislocated by Alpine tectonics. Subsidence history curves are therefore based on composite sections using data from several different localities. The comprehensive original sedimentary pile can be restored using precise palinspastic reconstructions (see Wildi et al. 1989).

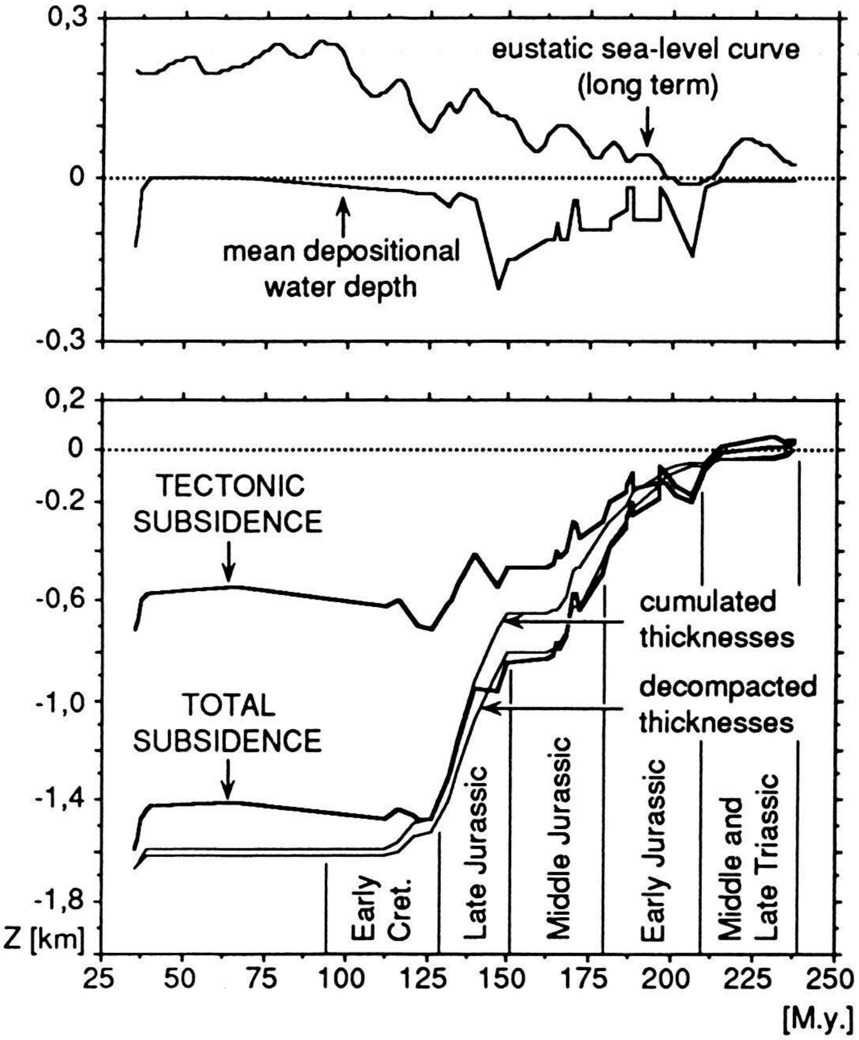

Fig. 3. Total versus tectonic subsidence (with decompaction, bathymetric and eustatic corrections; Ferdenrothorn section, long term sea-level curve from Haq et al. 1987, 1988). The influence of decompaction alone is also represented.

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[2]) Helvetic *sensu lato* refers here to a zone extending from the external basement massifs to the Wildhorn domain, excluding the Ultrahelvetic. Helvetic *sensu stricto* does not include these basement massifs and the Morcles and Doldenhorn infrahelvetic nappes (see Fig. 4).

2.2 Compaction

In our opinion, compaction is one of the most important parameters to consider in subsidence analysis: the shape of the corrected curve is very different from the uncorrected curve (Fig. 3).

Porosities are generally very low in the studied sediments: less than 5% in the Jura belt and less than 1 or 2% in the Helvetic zone. As indicated by porosity-depth relationships established in offshore wells (e.g. Sclater & Christie 1980, Bond & Kominz 1984, Baldwin & Butler 1985), these very low values cannot be totally explained by overburden and mechanical compaction. Porosity reduction is also due to cementation. Unfortunately, we are generally unable to determine the time of cementation, its duration or the origin of the pore fluids. In the Alpine context, data from literature are insufficient to allow systematic correction for early cementation, overpressuring, or other processes occurring during sediment diagenesis. As a consequence, a pragmatic and somewhat simplistic model of sediment compaction during burial has been chosen. We used the decompaction procedure proposed by Sclater & Christie (1980), where porosity is assumed to follow an exponential relationship with depth:

$$f = f_0 \cdot e^{-cz} \tag{1}$$

(f = porosity at any depth z; f_0 = porosity at the surface, or initial porosity [Table 1]; c = lithologic compaction coefficient [Table 1]; z = depth in kilometers).

The mechanical compaction considered here is an oversimplification of the natural complex compaction processes. Nevertheless, although the amplitude may change locally, the overall shape of the subsidence curves obtained with partial corrections (as here) is similar to the one obtained with more sophisticated corrections (e.g. Bond & Kominz 1984: "delithification procedure"; see also Morton 1987).

Table 1: Compaction variables.

Lithology	Initial porosity f_0 [%]	Lithologic coefficient c [km^{-1}]	Reference
limestone	45	0,54	Sawyer et al. (1982)
sandstone	49	0,27	Sclater & Christie (1980)
shales	63	0,51	Sclater & Christie (1980)
dolomite	31	0,22	Schmoker & Halley (1982) Heidlauf et al. (1986)
shaly sand	56	0,39	Sclater & Christie (1980)

2.3 *Tectonic deformation and erosion*

Alpine tectonics have strongly modified sediment thicknesses, especially in the Helvetic nappes *sensu lato*. In some instances, tectonic restoration using different strain markers has been performed through a complete section (e.g. Huggenberger 1985, for the Morcles nappe). But in most cases, data on tectonic deformation are very sporadic and concern only those parts of a section which contain strain markers (e.g. Schläppi 1980, Dolivo 1982, Burkhard 1988). The correction made here is based on such published studies. Personal field observations have been introduced in case of insufficient or lacking data.

If hiatuses are observed in a section, it is always difficult to interpret them in terms of non-deposition or erosion. If an erosion event can be established, the metric estimation of the missing section is even more delicate. However, a correction may be introduced in some situations (see Wildi et al. 1989).

2.4 Depositional water depth

Correction for depositional water depth is another key-parameter in subsidence analysis (Bertram & Milton 1988, Célérier 1988). Metric values are provided mainly by paleontological and paleoecological indicators, petrographic composition and preserved sedimentary structures. Bathymetric estimates are fairly reliable for sediments deposited above wave base where sedimentary structures occur. The rocks discussed here accumulated in shallow epicontinental seas throughout the Mesozoic and the errors due to bathymetric misinterpretation are thus considerably reduced. Data from literature have been used in this study (see Wildi et al. 1989). New sedimentological interpretations in the North-Helvetic realm of western Switzerland have been introduced for the Triassic and Lower Jurassic parts of the sections (Loup 1992a). Minimum and maximum water depths have been assigned to the base and top of each lithological unit, resulting in a minimum and a maximum subsidence curve.

2.5 Eustatic sea-level variations

The depth of a reference level at any time is given with respect to the coeval sea-level. An eustatic correction is necessary to bring all sampling points to the modern sea-level datum. Although the metric amplitudes of eustatic sea-level changes are still debated, the overall trend is generally confirmed by the different authors (references in Loup 1992a; see also Burton et al. 1987). For this study, metric corrections for eustatic sea-level changes are based on the long term curve of Haq et al. (1987, 1988). The use of the short term curve may introduce artefacts related to dating errors; moreover, the precise significance of this curve is more controversial (e.g. Hallam 1988).

2.6 Dating and time scale

In the study area, dating of sediments is based on biostratigraphic evidence. Unfortunately, biostratigraphic control is very uneven. Dating is then provided by lithologic and facies correlations; this can lead to substantial errors due to diachronous facies zones (see Wildi et al. 1989). Inaccurate dating will affect the slopes of the subsidence curves.

A time scale is needed to convert the biozonations into absolute ages. Important differences can be noted between the available charts (see Funk 1985, Morton 1987). Though the detailed shape of the curves may be modified (e.g. Fig. 4 in Funk 1985), the overall or long term subsidence is not much affected by the choice of the chronostratigraphic reference. The time scale and biostratigraphic zonal schemes used here are from Haq et al. (1987, 1988).

2.7 *Backstripping*

The backstripping procedure allows for the removal of the sediment loading effect on the basement (Figs. 2 and 3). The so-called "tectonic" subsidence is calculated by the equation developed by Steckler & Watts (1978), Sclater & Christie (1980) or Bond & Kominz (1984):

$$Y = \Phi\left\{S\left(\frac{\rho m - \rho s}{\rho m - \rho w}\right) - \Delta\,SL\left(\frac{\rho w}{\rho m - \rho w}\right)\right\} + (Wd - \Delta\,SL) \qquad (2)$$

Y = tectonic subsidence
Φ = basement response function
S = corrected sediment thickness
ρm = mean mantle density (3,33 g/cm^3)
ρs = mean bulk sediment density
ρw = water density (1 g/cm^3)
Wd = depositional water depth
Δ SL = sea-level change relative to present-day level.

The parameters in equation (2) have been discussed above (sections 2.2 to 2.5). The new factor Φ describes the response of the basement to overburden. Two end-member models are usually discussed: the load can be compensated either 1) locally by an Airy-type isostatic model (no lateral strength of the lithosphere) or 2) regionally by a deflection of the plate (non-zero lateral strength). In the latter model, the flexural rigidity through time can either increase (elastic plate) or decrease (visco-elastic or Maxwell plate; e.g. Watts et al. 1982).

For this study, the effects of sediment loading have been removed assuming Airy compensation, which means a basement response function Φ set equal to 1 in equation (2). Such an assumption can only be valid in the early stages of basin development when active faulting diminishes the lateral strength of the plate. For later phases, a flexural compensation with increasing lateral strength due to cooling of the lithosphere (Watts 1978) is more appropriate. Lateral heat transfer was also ignored. However, Steckler & Watts (1978, 1982), Watts & Steckler (1979) and Bond & Kominz (1984) have demonstrated that a 1D-model (Airy compensation throughout basin evolution without lateral heat loss) instead of a 2D-model (flexure and lateral heat flow) introduces only small differences in the amplitude (10 to 15%) but not in the shape of the subsidence curves.

2.8 *Studied sections (Fig. 4 and Table 2)*

The tectonic subsidence has been calculated for 57 different localities (23 from Wildi et al. 1989, reprocessed for tectonic subsidence, and 34 new ones, all located in the Helvetic realm, Loup 1992a; Table 2). These stratigraphic sections are restored to their original palinspastic location on Fig. 4, which allows studying the spatial distribution

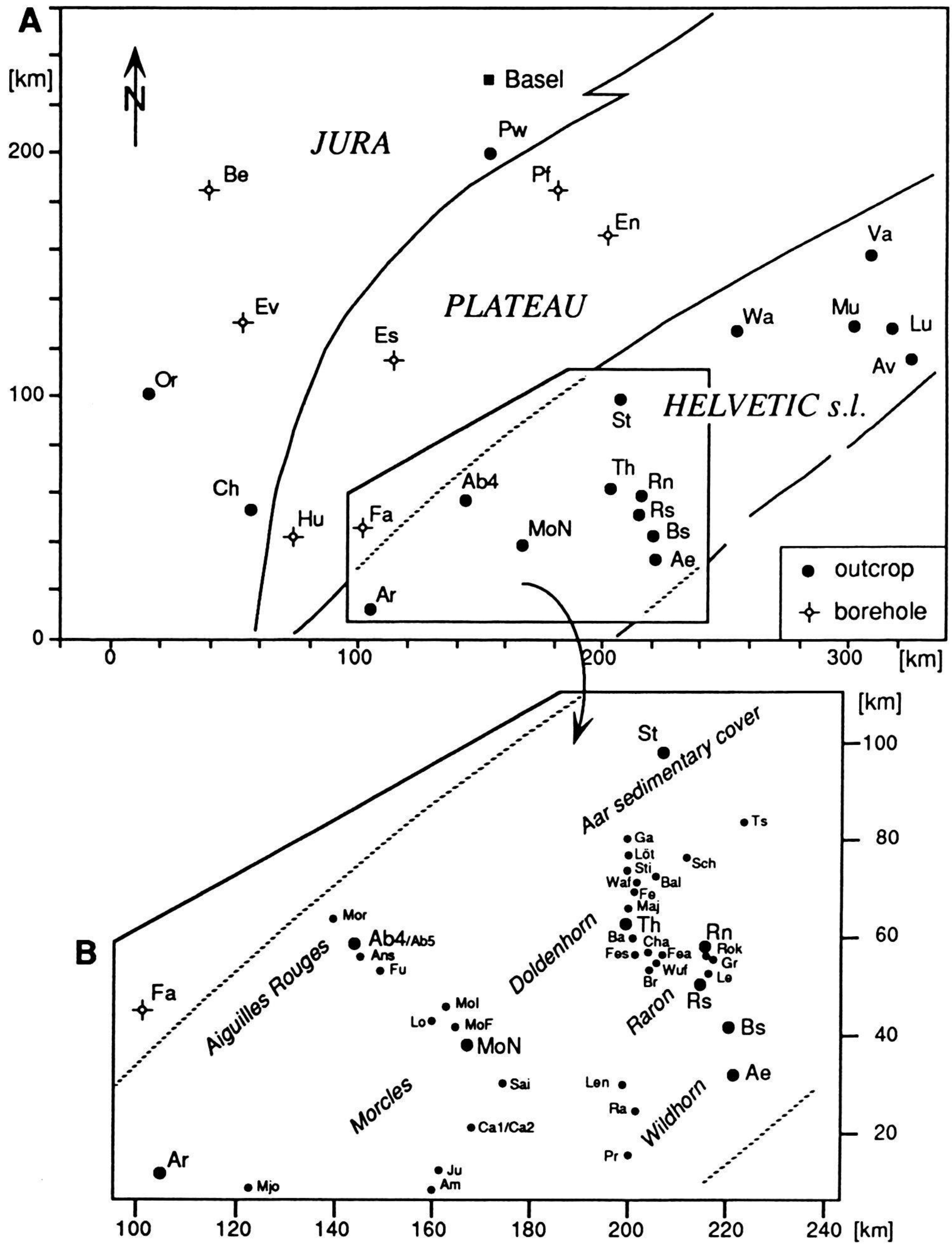


Fig. 4. Palinspastic position of the analyzed sections (see Table 2 for codes and coordinates): A: selection of profiles recalculated from Wildi et al. (1989, outcrop and borehole data) B: new profiles (small dots) from the Helvetic realm (Loup 1992a, outcrop data). The paleogeographic subdivisions used in the text are also indicated. The palinspastic base map is from Wildi et al. (1989); it has been augmented for the Helvetic realm of western Switzerland using the data of Trümpy (1971), Schläppi (1980), Dolivo (1982), Huggenberger (1985), Bugnon (1986), Zwahlen (1986), Moser (1987) and Burkhard (1988).

Table 2: Tectonic subsidence analysis: codes and coordinates of the sections (CH: Switzerland; FR: France).

Code	Name	Coordinates	Code	Name	Coordinates
Ab4	Arbignon 4	CH 571.3/115.2	Lo	Longeraie	CH 580/113.4
Ab5	Arbignon 5	CH 571.3/115.2	Löt	Lötschepass	CH 621.3/140.6
Ae	Aermighorn	CH 621/154.5	Lu	Lüsis	CH 745/234
		and 595/124	Maj	Majinghorn	CH 619/137
Am	Amône	CH 573.5/88	Mjo	Mont Joly	FR 542/750
Ans	Arbignon	CH 568/114	MoF	Morcles (front)	CH 575/119
Av	Alvier	CH 748/219	MoI	idem (inv. flank)	CH 575/114
Ba	Bachalp	CH 619/134	MoN	idem (norm. fl.)	CH 582/116
Bal	Balm	CH 620.9/142.5	Mor	Morcles-village	CH 569/118
Be	Besançon	FR 875/255	Mu	Mürtschen	CH 730/215
Br	Bratsch	CH 620.5/129.6	Or	Orgelet le B.	FR 850/177
Bs	Bundstock	CH 623.5/152.5	Pf	Pfaffnau 1	CH 632/231
Ca1	Catogne 1	CH 575/100	Pr	Prabé	CH 593/126
Ca2	Catogne 2	CH 575/100	Pw	Passwang	CH 615/246
Ch	Champfromier	FR 868/138	Ra	Rawil	CH 600/137
Cha	Chalberfärich	CH 620.6/132	Rn	Raron North	CH 633.3/132.6
En	Entlebuch 1	CH 651/202	Rok	Rotekuh	CH 632.6/132.6
Es	Essertines 1	CH 539/173	Rs	Raron South	CH 630/130
Ev	Essavilly 101	FR 885/205	Sai	Saillon	CH 580/113
Fa	Faucigny 1	FR 911/132	Sch	Schwarzdolde	CH 623.7/145.6
Fe	Ferdenrothorn	CH 621/139	St	Stechelberg	CH 636/155.2
Fea	Feselalp	CH 622.3/132.6			to 633.3/154.6
Fes	Feschel	CH 619/130	Sti	Stierstutz	CH 621.7/140
Fu	Fully	CH 574/115	Th	Torrenthorn	CH 620/134
Ga	Gastern	CH 623/145			to 612/139.3
Gr	Grieläger	CH 632/132	To	Toillon 1	FR 881/196
Hu	Humilly 2	FR 885/130	Ts	Tschingelgrat	CH 632/151
Ju	Jurette	CH 574/90.3	Va	Vättis	CH 752/198
Le	Leiggern	CH 631/130	Waf	Wandfluh	CH 621.5/139.5
Len	Lenk	CH 600/145	Wuf	Wildi-Uflänge	CH 622.1/131.2

of Mesozoic subsidence patterns. The stratigraphic data used for the reconstruction of the profiles come from literature (well reports, explanation notes to geological maps, regional studies; see Wildi et al. 1989, Loup 1992a for detailed references) and from personal field work.

Despite the simplifications, problems and possible errors intervening in the subsidence analysis, a coherent approach makes comparison between different curves qualitatively possible. Quantitative comparison is more hypothetical and must be carried out carefully.

3. Basin-forming mechanisms

The formation of sedimentary basins can be seen as a response to definitive or temporary modifications of the thermo-mechanical structure of the lithosphere (review and references in Allen & Allen 1990).

Stretching mechanisms controlled the Mesozoic breakup of the Permo-Triassic Pangea and the initial stages of the Ligurian Tethys evolution, until oceanic crust and lithosphere were formed (e.g. Laubscher & Bernoulli 1977). Other processes (e.g. strike-slip movements) were probably also involved but only as superimposed on the main extensional component.

3.1 Uniform stretching

The uniform stretching model of McKenzie (1978) (Fig. 5A) has found numerous applications and has served as a starting point for a wide range of more complex models. The model's premises are: uniform and instantaneous extension of all lithospheric layers, constant Airy isostasy, vertical heat transfer and absence of radioactive heat source (1D-model). Extension has two consequences: failure of the crust and upward migration of the lithosphere-asthenosphere boundary inducing thermal anomaly. Two subsidence components can thus be separated (Fig. 5A): instantaneous initial or fault-controlled subsidence and long-term thermal subsidence (decay of the thermal anomaly).

This model has been successfully applied to the North Sea (Sclater & Christie 1980, Barton & Wood 1984), passive continental margins (Royden & Keen 1980, Royden et al. 1980, Le Pichon et al. 1982, Sawyer et al. 1982, Issler & Beaumont 1987) and intracratonic basins (Sclater et al. 1980, Brunet & Le Pichon 1982). However, the uniform stretching model is unable to explain the subsidence observed in many other intracratonic basins and passive margins. Variations on this first model had to be developed.

3.2 Non-uniform (or depth-dependent) discontinuous stretching

In this model (Figs. 5B and 5C), extension is a function of depth: the upper and lower lithospheric layers are thinned differentially (Royden & Keen 1980, Sclater et al. 1980, Hellinger & Sclater 1983, Royden et al. 1983). A detachment surface or "discontinuity" running in or at the base of the crust (Moho), or in the subcrustal lithosphere is assumed to separate the two levels. In practical applications, the crust usually represents the upper level (stretching factor δ), and the subcrustal lithosphere or lithospheric mantle corresponds to the lower level (stretching factor β). Two situations can be considered:

1) The crustal stretching model ($\delta > \beta$) is characterized by a small thermal anomaly as shown by the depth-temperature diagram of Figure 5B. In contrast to the uniform stretching model, the predicted initial subsidence is higher whereas the thermal component is reduced. The subsidence of several basins has been explained by this model: center of the Pattani Trough (Hellinger & Sclater 1983), Vienna Basin (Royden et al. 1983), Ridge Basin (Karner & Dewey 1986) and Wessex Basin (Karner et al. 1987).
2) The subcrustal extension model ($\delta < \beta$) is characterized by a major thermal anomaly (Fig. 5C). Consequently, the thermal subsidence component is much larger than predicted by the other two models; the initial subsidence component is much diminished. This model can explain the subsidence in the Labrador Margin (Royden & Keen 1980), the central intra-Carpathian basins (Sclater et al. 1980), the Pannonian Basin (Royden et al. 1983) and in the northern part of the Dutch Central Graben (Kooi et al. 1989).

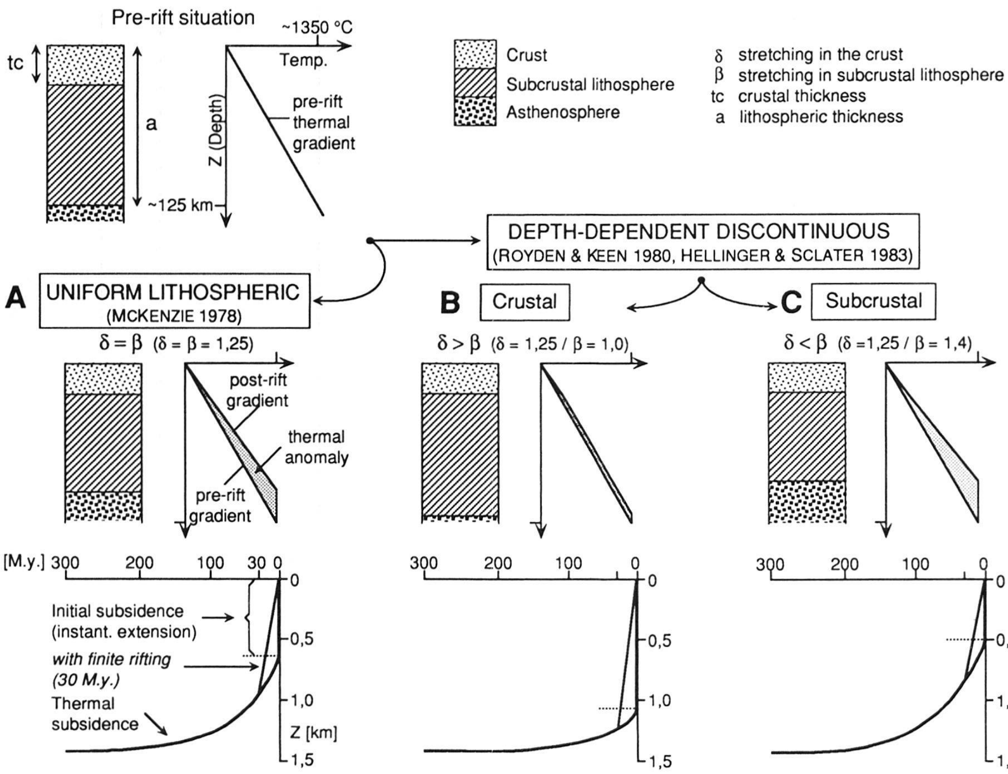


Fig. 5. Tectonic subsidence curves predicted by the uniform and by the depth-dependent discontinuous stretching models. The thicknesses of the crust and subcrustal lithosphere and the temperature-depth profile are drawn for each stretching mechanism. The resulting subsidence curve is represented for both the instantaneous stretching solution and the finite rifting solution (with cooling during extension). See text for further discussion. Modified from Loup (1992 b).

Three problems are implicitly bound to the depth-dependent discontinuous stretching model: 1) the detachment required is not systematically proven, 2) the different stretching factors imply a space problem ("strain compatibility", e.g. Karner & Dewey 1986, Karner et al. 1987), and 3) a process causing differential stretching of the lithosphere has to be found.

The main interest of these three models is to predict variable partitioning of the two subsidence components. The stretching factor in the crust determines the value of the final subsidence: equivalent asymptotic values are obtained for all three models if identical stretching factors δ are used ($\delta = 1{,}25$, or 25%, in Fig. 5). Thinning of the subcrustal lithosphere ($\beta = 0$, $\beta = 1{,}25$, $\beta = 1{,}4$ in Fig. 5) determines the partitioning of the two components, or the curve's path between the beginning of rifting and the end of subsidence.

3.3 Formulation and lithospheric parameters

The theoretical subsidence curves were computed according to the formulas of Hellinger & Sclater (1983). For $\delta = \beta$ (uniform stretching), the equations reduce to the form developed by McKenzie (1978), as corrected by Jarvis & McKenzie (1980) and Sclater & Christie (1980). The model's premises are: the Moho as decoupling horizon and an Airy-type compensation of the basement without lateral heat flow (1D-model).

The uniform stretching model and its variations assume instantaneous rifting. In the Western Alps, rifting lasted at least 30 M.y., with a maximum value of 70 M.y. (e.g. Boillot et al. 1984). Models were therefore calculated with variable rifting periods allowing cooling during extension (see Jarvis & McKenzie 1980 and Cochran 1983 for extended discussion). Subsidence was set to 0 at the beginning of rifting, and equal to the tectonic subsidence (fault-controlled plus thermal components) at the time corresponding to the end of the rifting period. Between these two points, subsidence was considered as linear (Fig. 5). This is a slight approximation with respect to the curves established using Cochran's (1983) formulas.

The values of the pre-rift thicknesses of the crust and lithosphere must be chosen carefully as their influence on the theoretical curves is significant. This requirement is satisfactorily fulfilled by geophysical prospecting in undeformed counterparts of continental margins or cratonic basins. However, in the situation of tectonized areas, pre-extension crustal and lithospheric thicknesses must be determined by comparison with present values of nearby undeformed zones. In the stable European foreland, these values are respectively 25 to 35 km and 70 to 130 km (Müller et al. 1980, Panza et al. 1984, Freeman & Müller 1990). These numbers are consistent with the standard theoretical thicknesses of 31,2 and 125 km (Cochran 1981, Dewey 1982) which are adopted here for model computations. The other lithospheric parameters are listed in Table 3.

4. Tectonic subsidence

The total subsidence has been discussed in detail by Wildi et al. (1989), who also give six map representations of the subsidence rates from Middle-Late Triassic to "Middle" Cretaceous times (see also Fig. 7.12 in Loup 1992a). The total subsidence reflects the complex interaction of parameters varying through time (sediment supply,

Table 3: Parameters considered for computation of the theoretical curves (mostly from Parsons & Sclater 1977).

Parameter		Value	Definition
ρm	=	3,33 g/cm^3	mean mantle density at 0 °C
ρc	=	2,8 g/cm^3	mean crust density at 0 °C
ρw	=	1,0 g/cm^3	water density
Tm	=	1333 °C	temperature at base of lithosphere
α	=	3,28 x 10^{-5} °C^{-1}	thermal expansion coefficient
τ	=	62,8 M.y.	thermal time constant
tc	=	31,2 km	initial thickness of the continental crust (e.g. COCHRAN 1981)
a	=	125 km	initial thickness of the lithosphere (e.g. COCHRAN 1981)

bathymetric changes and real movements of the basement). By contrast, the tectonic subsidence can help finding possible basin-forming mechanisms. The following discussion therefore focuses on the tectonic subsidence only; all indicated rates are tectonic subsidence rates.

Figure 6 comprises a selection of curves which allows the recognition of seven distinct provinces characterized by a comparable subsidence pattern (similar shapes and amplitudes, identical number and succession of subsidence phases through time). These provinces do not necessarily correspond to paleogeographic domains. Their discussion (sections 4.1 to 4.7) follows roughly a counterclockwise path from the north to the east of the study area. One or two detailed curves for each group are presented on Figure 7 and subsidence phases are summarized in Figure 8.

4.1 Passwang [Pw], Pfaffnau [Pf] and Entlebuch [En]; Besançon [Be]

This first group crosses the Jura-Plateau boundary (Fig. 6). Subsidence exponentially decreased from the Triassic to the Jurassic. The Besançon profile diverges slightly from this pattern with an almost linear subsidence from the Early Triassic until the Barremian (with slight uplift). The total values of tectonic subsidence range between 150 and 500 m, 60% of these amplitudes occurring during the Triassic. Two phases can be distinguished (Fig. 7A):

- the main phase lasted about 70 M.y., from the Middle and Late Triassic (subsidence) to the Late Liassic (no subsidence, or 'plateau');
- a second, minor and shorter (< 30 M.y.) phase began in the early Middle Jurassic, or in the mid-Late Jurassic depending on the section.

4.2 Orgelet-le-Bourget [Or], Essavilly [Ev], Essertines [Es] and Humilly [Hu]

The second group also covers locations from the Jura and Plateau (Fig. 6), but shows higher final tectonic subsidence values (from 650 to 1100 m). The Middle and

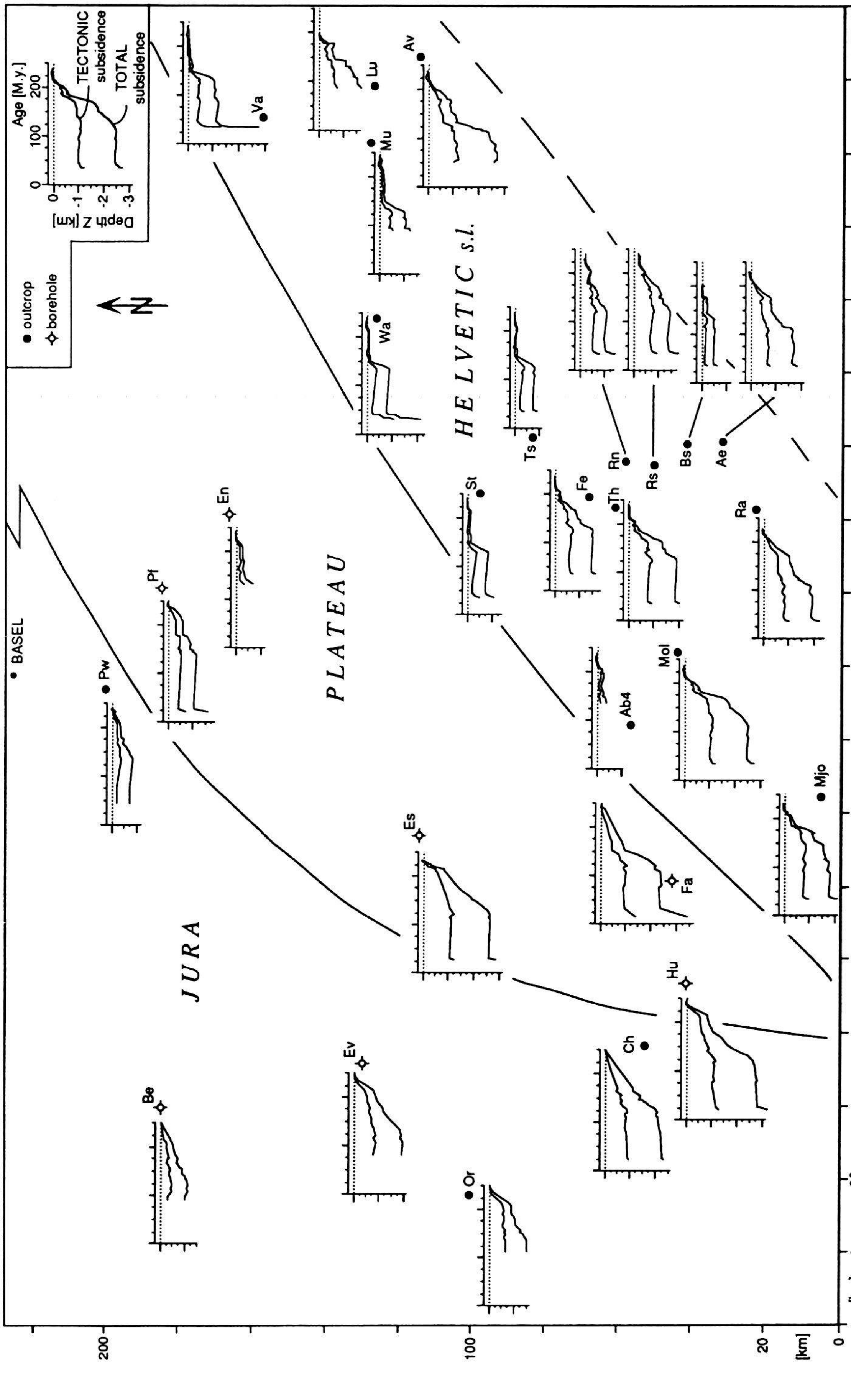


Fig. 6. Total and tectonic subsidence curves of 27 representative sections. Profiles are restored to their palinspastic position and drawn for mean depositional water depth.

Late Triassic history is similar in all 4 sections: 50 to 80% of the tectonic subsidence was "linearly" acquired in a period of 25 to 30 M.y. (rate of 15–22 mm/1000 y). By contrast, the Jurassic-Cretaceous history is variable:

- in the Orgelet-le-Bourget [Or] profile, subsidence was very slow from Late Triassic to early Cretaceous times, with only some minor undulations during the Middle Jurassic (Fig. 7C);
- in the other 3 sections, a renewed, but minor subsidence phase began in the Early or Middle Jurassic, with linear or increasing subsidence until the Early Cretaceous (rates from 3 to 10 mm/1000 y; Fig. 7B).

4.3 Champfromier [Ch] and Faucigny [Fa]

The shape and final values of tectonic subsidence (around 1000 m) of these two profiles are very similar, though one is located in the Jura, the other in the Plateau (Fig. 6). Two phases can be separated (Fig. 7D):

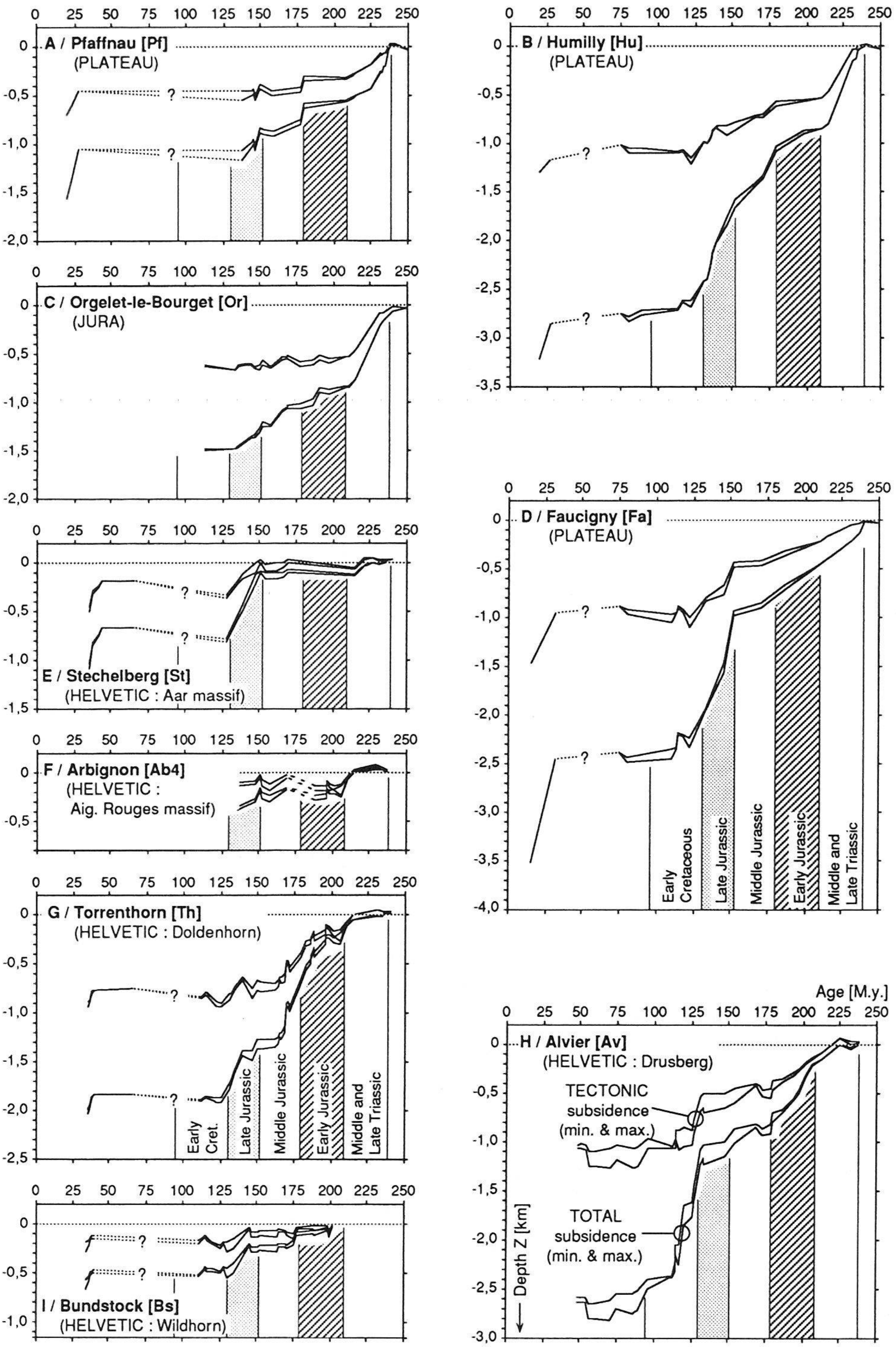
- a prolonged linear subsidence occurred between the Early Triassic and the Middle Jurassic (5–6 mm/1000 y); the linearity could be related to the scarcity of sampling points during this period;
- a second and more rapid phase showing decreasing subsidence rates lasted from the Late Jurassic to the mid-Early Cretaceous.

4.4 Stechelberg [St], Tschingelgrat [Ts], Wanneli [Wa], Vättis [Va] and Mürtschen [Mu]; Arbignon [Ab4]

This group comprises sections from the northernmost part of the Helvetic realm *sensu lato* (Fig. 6). The first four are taken atop the northern Aar massif. The Mürtschen section represents the basal Helvetic nappe of Eastern Switzerland. After a minor-amplitude and short-lived subsidence phase during the Middle and Late Triassic, a long plateau with only small undulations characterized the Early and Middle Jurassic periods (Fig. 7E). The major phase began in the early Late Jurassic and ended in the Latest Jurassic or Earliest Cretaceous. The complete tectonic subsidence (300 to 500 m) was thus acquired in 20 to 25 M.y. (rates between 12 and 20 mm/1000 y). The shape of the curve is variable, indicating increasing or decreasing subsidence rates.

The Arbignon section (Fig. 7F) is taken from the unique remnant of a more widely deposited Lower Jurassic cover on the Aiguilles Rouges massif (discussion in Loup 1992a). It departs from the simple pattern mentioned above. The Late Triassic subsidence continued until the Hettangian (maximum rate of 18 mm/1000 y) and was followed by a plateau during the Sinemurian and Early Pliensbachian. The Late Jurassic phase can be observed in nearby profiles.

Fig. 7. Selection of detailed curves, with minimum and maximum bathymetry (see section Alvier for the caption). The dotted segments of the curves correspond to the main hiatuses (principally Late Cretaceous – Early Tertiary).


A / Pfaffnau [Pf]
(PLATEAU)
B / Humilly [Hu]
(PLATEAU)
C / Orgelet-le-Bourget [Or]
(JURA)
D / Faucigny [Fa]
(PLATEAU)
E / Stechelberg [St]
(HELVETIC : Aar massif)
F / Arbignon [Ab4]
(HELVETIC :
Aig. Rouges massif)
G / Torrenthorn [Th]
(HELVETIC : Doldenhorn)
H / Alvier [Av]
(HELVETIC : Drusberg)
I / Bundstock [Bs]
(HELVETIC : Wildhorn)
Early Cretaceous
Early Cret.
Late Jurassic
Middle Jurassic
Early Jurassic
Middle and Late Triassic
Age [M.y.]
Depth Z [km]
TECTONIC subsidence (min. & max.)
TOTAL subsidence (min. & max.)
0
25
50
75
100
125
150
175
200
225
250
0
-0,5
-1,0
-1,5
-2,0
-2,5
-3,0
-3,5
-4,0
?

4.5 *Mont Joly [Mjo], Morcles [Mol], Torrenthorn [Th], Ferdenrothorn [Fe], Raron North [Rn], Raron South [Rs]*

This group depicts the tectonic subsidence pattern on the external Mont Blanc massif (Morcles infrahelvetic nappe) and on the western Aar massif transect (Doldenhorn infrahelvetic nappe to Raron syncline; Figs. 4 and 6). Although some disparities are noted from one profile to another (time-lag between phases, number or intensity of phases), the successive events are generally similar. The maximum final subsidence reaches 1100 m (Morcles nappe). The general subsidence pattern is illustrated by the Torrenthorn section (Figs. 7G and 8):

- subsidence increased from Late Triassic to Early Jurassic (Hettangian) times; no tectonic subsidence was recorded between the Sinemurian and the Pliensbachian;
- the major subsidence phase lasted from the late Early Jurassic (Toarcian) until the Middle Jurassic (Bajocian) (max. rate of 20 mm/1000 y); the late Middle Jurassic to early Late Jurassic are represented by a plateau;
- a renewed subsidence phase occurred during the mid-Late Jurassic and the early Cretaceous (Valanginian).

The Mont Joly and Morcles profiles differ slightly from the Aar transect sections. The major phase, even stronger here, began in the latest Early Jurassic and was restricted to the Aalenian. The Late Jurassic phase was attenuated.

4.6 *Rawil [Ra], Aermighorn [Ae] and Alvier [Av]*

These sections are located in the Helvetic realm *sensu stricto:* Wildhorn for 'Rawil' and 'Aermighorn', Drusberg for 'Alvier'. This group is very homogeneous (Fig. 6). The tectonic subsidence reaches 750 to 1100 m and is subdivided as follows (Figs. 7H and 8):

- a linear subsidence phase occurred between Late Triassic and late Early Jurassic times (mean rate of 10 mm/1000 y); sufficient information regarding stratigraphy, thicknesses and depositional water depths is however lacking for this interval;
- no or slow subsidence (max. rates of 3 mm/1000 y) was recorded during the Middle and Late Jurassic;
- the major phase, with increasing subsidence rates in some profiles, took place during the Early Cretaceous (Berriasian-Valanginian; rates from 10 to 20 mm/1000 y, up to 60 mm/1000 y).

The late Jurassic event present in many other groups of sections is not observed here.

4.7 *Isolated sections: Bundstock [Bu] and Lüsis [Lu]*

The Bundstock profile (Fig. 7I) corresponds to a North-Wildhorn position. It shows similarities with the Stechelberg group (section 4.4), i.e. by a marked subsidence in Late Jurassic. However, distinct short-lived phases occurred during the Early and Middle Jurassic.

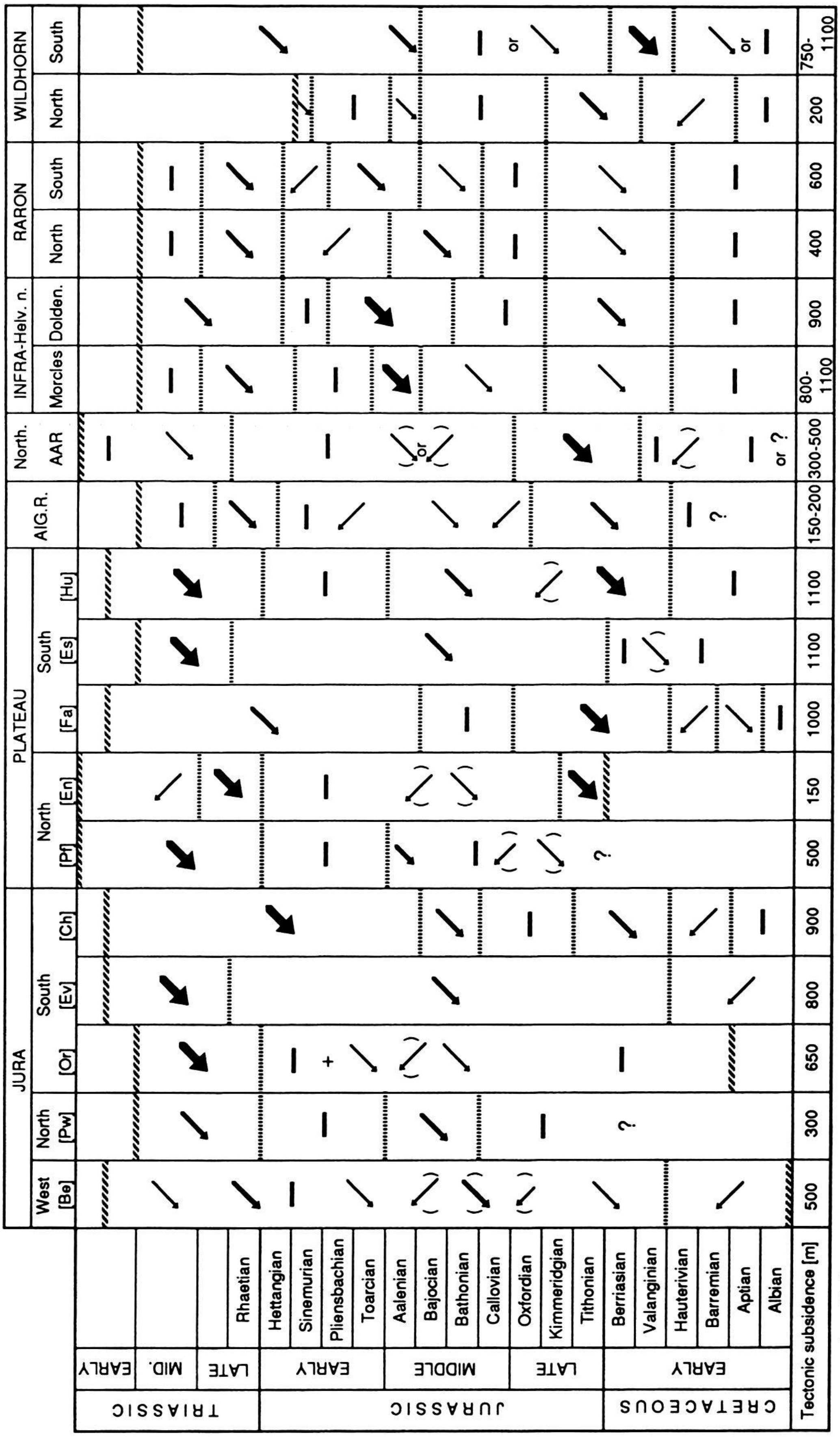


Fig. 8. Main and secondary Mesozoic tectonic subsidence phases from the Jura to the Helvetic realm. The values of the tectonic subsidence before basin inversion are also indicated.

The subsidence of the Lüsis section (see Trümpy 1969, Funk 1985 for paleogeography) was mainly linear between the Sinemurian and the Early Cretaceous (rate of 5–6 mm/1000 y). Two short-lived accelerations occurred during the Aalenian and the Late Jurassic. As such, this section shows the closest similarity to the Morcles/Torrenthorn group (section 4.5).

4.8 Conclusions from the tectonic subsidence analysis

The main outcomes of the tectonic subsidence analysis can be summarized as follows:

1) No overall picture of the Mesozoic subsidence can be drawn over the study area (Fig. 8):
- different subsidence patterns are observed within each paleogeographic domain: the number, timing, duration and form of the several phases vary significantly from place to place;
- similar subsidence patterns can cross paleogeographic boundaries and are found in both the Jura and Plateau domains. Thus the basin-forming mechanisms and the tectonic inversion processes are not necessarily linked;
- in the Helvetic realm however, the zones of comparable subsidence modes correspond more or less to the Alpine tectonic units: a mean subsidence pattern can be found for each subdomain.

2) The initiation of subsidence appears to have varied in time, beginning usually in the late Early to Middle Triassic in the Jura and Swiss Plateau, only in the Late Triassic to Early Jurassic in the Helvetic realm.
3) Three basic subsidence trends are observed: concave-upward (progressively decreasing subsidence rates), linear (constant rate) and convex-upward cycles (progressively increasing rates). The first two are the most common for phases up to the end of the Jurassic; the Early Cretaceous phase shows principally a convex-upward trend.
4) The 'main' or best defined subsidence events, that is those with the highest subsidence rates and distinct beginning and end, were recorded during (Fig. 8):
- the late Early to Late Triassic in the Jura and Plateau;
- the Late Jurassic on the Aiguilles Rouges and Aar external massifs;
- the late Early Jurassic and the early Middle Jurassic in the Morcles-Doldenhorn area;
- the Early Cretaceous in the Wildhorn and South-Helvetic domain.

5) The subsidence is polyphase and cannot be described by a single event or a continuous process. Several short term phases (called here '2nd order phases'), with a mean duration of 50 to 60 M.y., are superimposed on the long term Mesozoic subsidence ('1st order', with a duration longer than 100 to 150 M.y.). Other shorter-lived events ('3rd order' and higher?) seem to be in turn superimposed on the 2nd order subsidence. The resolution of the method in the Alpine context is insufficient to properly investigate these higher frequencies.

Some of the observed discrepancies between neighboring profiles (uplift versus subsidence, variable amplitudes, timing or shape of the cycles) could be a response to different situations in the basin. In the presence of inverted domains, the precise extensional geometry is unknown and the influence of the position along the margin cannot be assessed.

The observed polyphase tectonic subsidence brings up a fundamental alternative:

- "one-rifting hypothesis": a single rifting event or thermo-mechanical modification of the lithosphere is able to generate a curve similar to the reconstructed Mesozoic 1^{st} order subsidence. The 2^{nd} order phases, or deviations from the 1^{st} order envelope, are then related to another kind of processes superimposed on the rifting-induced subsidence (e.g. major variations of the in-plane stress regime);
- "re-rifting hypothesis" (see also Karner et al. 1987): several successive modifications of the lithosphere are needed to reproduce the reconstructed tectonic subsidence. An appropriate model of lithospheric stretching must be found for each 2^{nd} order phase. The 1^{st} order trend is then an artefact that does not correspond to a subsidence-driving mechanism.

In order to solve this dilemma, the 1^{st} and 2^{nd} order phases of the reconstructed tectonic subsidence are now compared to the three models of lithospheric extension.

5. Tectonic subsidence and stretching models

5.1 Preliminary remarks

Although theoretically simple, this comparison is not straightforward and some restrictions must be emphasized:

- the suggested stretching mechanism is a 'non-unique' solution: another model derived from the three previously discussed, but calculated with different lithospheric parameters, or other more complex or unexplored processes, may also generate the observed subsidence;
- due to the uncertainties and simplifications in the geohistory analysis (section 2) and in the calculation of the theoretical curves (section 3), the suggested stretching factors must be taken as relative values. However, as a similar approach has been applied systematically, the qualitative results and the relative differences between sections can be considered as 'true'.

Stretching in the crust (δ) is given by matching the asymptotic values of both the reconstructed tectonic subsidence curve (before the Alpine inversion) and the modelled curves. The amount of stretching in the lower lithosphere (β) and the rifting period (Δt) are then given by the theoretical curve showing the best correlation with the reconstructed subsidence between beginning of rifting and final subsidence. The resulting couple of $\delta - \beta$ values determines the nature of the lithospheric stretching.

Some difficulties arose in finding a plausible model for the two subsidence orders.

1^{st} order subsidence. A crustal stretching factor can be found for any situation, provided subsidence ends up with a plateau. However, the path between the starting point of subsidence and its final value cannot always be assigned to a curve:

- the subsidence is almost linear throughout and unrealistic rifting periods Δt (from 80 up to 130 M.y.) have to be applied. This is for example observed in the Besançon [Be], Champfromier [Ch] and Raron North [Rn] profiles;
- subsidence is made of long linear segments: only a very broad envelope can be found;
- the reconstructed tectonic subsidence deviates much (up to 400 m) from a 'best'-fitting curve (e.g. Humilly [Hu] profile, Fig. 9 B);
- some profiles are strictly linear and do not end with a plateau: no model can be determined.

2nd order subsidence. These phases are more easily characterized (Fig. 9 B shows how 2nd order phases are modelled). The obtained β and Δt pairs are always realistic and in agreement with the geodynamics of the Alpine Tethys. Some phases do not end with a plateau and no model can reasonably be found. The main difficulty comes here from the phases with increasing subsidence rates. Their beginning is difficult to assess, and such convex-upward cycles (related to flexure loading according to Vail et al. 1991) cannot fall into the modelled mechanisms whose components are either linear (approximation of the slightly concave-upward initial subsidence, see section 3.3) or concave-upward (thermal relaxation).

5.2 Jura (Fig. 9 A and Table 4)

The 1st order subsidence may be explained by uniform extension for Passwang, crustal stretching for Orgelet-le-Bourget (Fig. 9 A), and by subcrustal extension for Besançon and Essavilly (decoupling up to 17%, but abnormal rifting period Δt for Besançon and very poor correlation for Essavilly). No model can reasonably be found for Champfromier. The 2nd order phases are modelled by crustal extension (Essavilly) and by uniform stretching (Table 4).

The density of profiles is insufficient to draw definitive conclusions for the Jura. Subsidence mechanisms seem, however, to be very heterogeneous. The two clearly defined profiles (Essavilly and Orgelet-le-Bourget) suggest a high implication of the crust during extension that could correspond to the rejuvenation of Variscan structures. These two curves are also in agreement with the subsidence pattern typical of strike-slip related basins (pull-aparts), as proposed for example by Christie-Blick & Biddle (1985).

5.3 Plateau (Fig. 9 B and Table 4)

The 1st order subsidence may be modelled by subcrustal extension for 3 profiles (Essertines, Humilly, Pfaffnau). No final plateau is drawn in Entlebuch while Faucigny is poorly defined. Stretching factors are higher in the SW than in the NE part of the Plateau.

Fig. 9. Selection of profiles showing the comparison between tectonic subsidence curves and stretching models of the lithosphere (1st order subsidence only in A, C, D and E; 1st and 2nd orders in B and F). The dotted segments of the curves correspond to main hiatuses. The term 'rifting' refers to the rifting period Δt as suggested by the models, and not to the duration of the considered subsidence phase. See section Rawil for the caption.

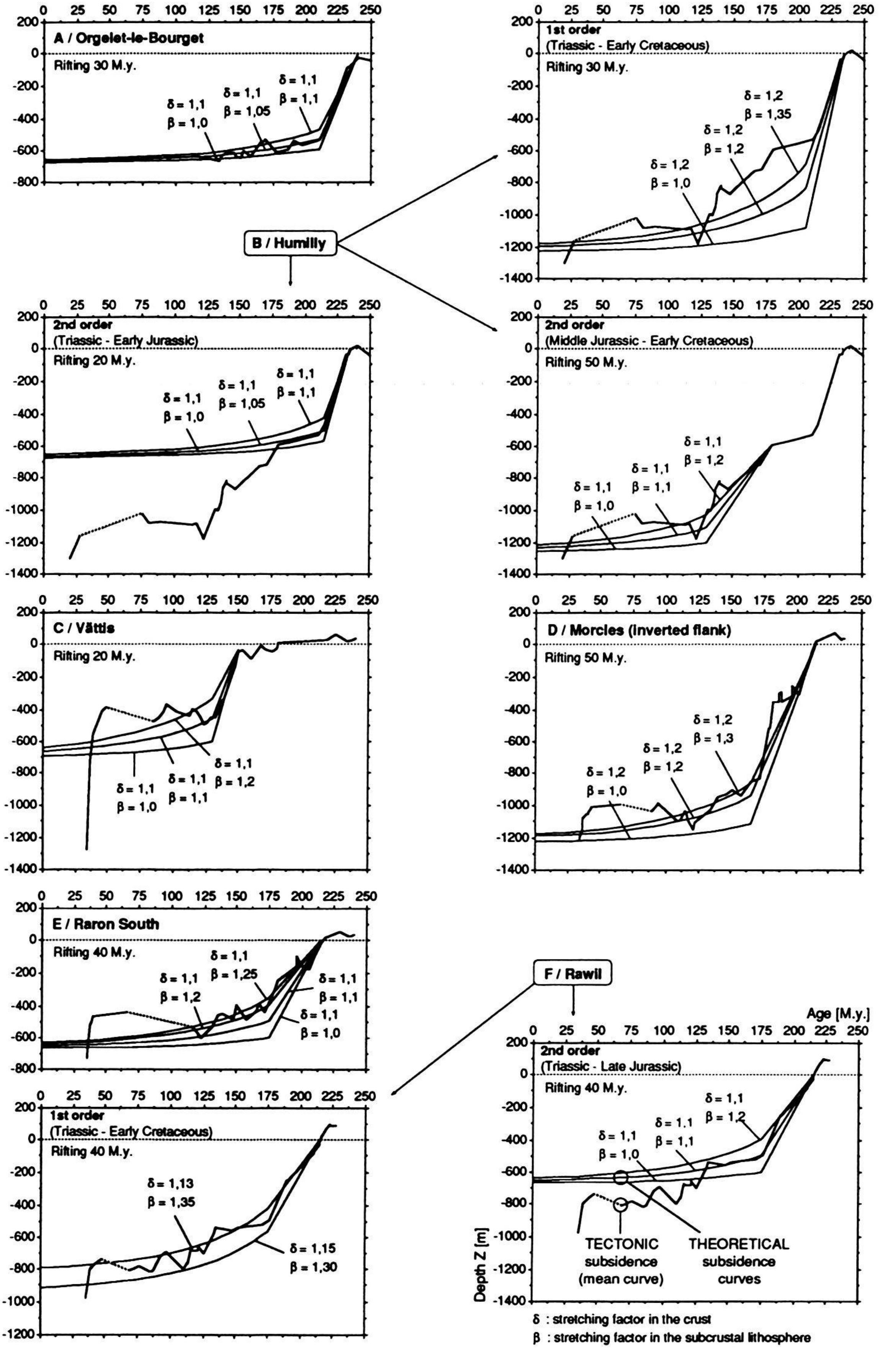

A / Orgelet-le-Bourget
Rifting 30 M.y.
δ = 1,1
β = 1,0
δ = 1,1
β = 1,05
δ = 1,1
β = 1,1
B / Humilly
1st order
(Triassic - Early Cretaceous)
Rifting 30 M.y.
δ = 1,2
β = 1,0
δ = 1,2
β = 1,2
δ = 1,2
β = 1,35
2nd order
(Triassic - Early Jurassic)
Rifting 20 M.y.
δ = 1,1
β = 1,0
δ = 1,1
β = 1,05
δ = 1,1
β = 1,1
2nd order
(Middle Jurassic - Early Cretaceous)
Rifting 50 M.y.
δ = 1,1
β = 1,0
δ = 1,1
β = 1,1
δ = 1,1
β = 1,2
C / Vättis
Rifting 20 M.y.
δ = 1,1
β = 1,0
δ = 1,1
β = 1,1
δ = 1,1
β = 1,2
D / Morcles (inverted flank)
Rifting 50 M.y.
δ = 1,2
β = 1,0
δ = 1,2
β = 1,2
δ = 1,2
β = 1,3
E / Raron South
Rifting 40 M.y.
δ = 1,1
β = 1,2
δ = 1,1
β = 1,25
δ = 1,1
β = 1,1
δ = 1,1
β = 1,0
1st order
(Triassic - Early Cretaceous)
Rifting 40 M.y.
δ = 1,13
β = 1,35
δ = 1,15
β = 1,30
F / Rawil
Age [M.y.]
2nd order
(Triassic - Late Jurassic)
Rifting 40 M.y.
δ = 1,1
β = 1,0
δ = 1,1
β = 1,1
δ = 1,1
β = 1,2
Depth Z [m]
TECTONIC
subsidence
(mean curve)
THEORETICAL
subsidence
curves
δ : stretching factor in the crust
β : stretching factor in the subcrustal lithosphere

Table 4: Subsidence-driving mechanisms for the 1st and 2nd order phases. In bold face: highest stretching factor of each δ/β pair. (δ: stretching in the crust; β: stretching in the subcrustal lithosphere; Δt: rifting period [M.y.]; epoch: time interval of the phase considered; ?: no appropriate stretching factor or model; ??: poorly defined phase (no realistic model); Jur.: Jurassic; Cret.: Cretaceous; E, M, L: Early, Middle, Late). Δt refers to the length of the rifting period as suggested by the models, and not to the duration of the complete subsidence phase considered.

Section	Code	FIRST ORDER				SECOND ORDER							
		δ	β	Δt	epoch	δ	β	Δt	epoch	δ	β	Δt	epoch
JURA													
Besançon	Be	1,07	**1,15**	125	Triassic - L.Jur.	-	-	-		-	-	-	
Champfromier	Ch	1,15	**?**		Triassic - E.Cret.	1,05	1,05	40	M.Jur. - E.Cret.	-	-	-	
Essavilly	Ev	1,13	**1,3**	30	Triassic - E.Cret.	**1,1**	1,05	30	M.Triassic - E.Jur.	-	-	-	
Orgelet-le-B.	Or	**1,1**	1,05	30	M.Triassic - E.Cret.	-	-	-		-	-	-	
Passwang	Pw	1,05	1,05	30	M.Triassic - L.Jur.	1,04	1,04	20	M.Triassic - E.Jur.		??		M.Jur.
PLATEAU													
Entlebuch	En		??		M.Triassic - ?	**1,03**	1,0	20	M.Triassic - M.Jur.		??		L.Jur.
Essertines	Es	1,2	**1,35**	10	L.Triassic - E.Cret.	-	-	-		-	-	-	
Faucigny	Fa	1,15	**?**		Triassic - E.Cret.	1,1	**1,25**	60	Triassic - M.Jur.	1,1	1,1	30	L.Jur. - E.Cret.
Humilly	Hu	1,2	**1,35**	30	Triassic - E.Cret.	**1,1**	1,05	20	Triassic - E.Jur.	1,1	**1,2**	50	M.Jur. - E.Cret.
Pfaffnau	Pf	1,1	**1,25**	30	Triassic - M.Jur.	**1,05**	1,0	30	M.Triassic - E.Jur.		??		M.Jur.
AIGUILLES ROUGES and northern AAR massifs													
Arbignon	Ab4	-	-	-		1,03	1,03	20	L.Triassic - E.Jur.	-	-	-	
Morcles (town)	Mor	-	-	-		1,03	1,03	20	L.Triassic - E.Jur.	1,03	1,03	30	L.Jur. - E.Cret.
Stechelberg	St	-	-	-		1,07	1,07	20	L.Jur.	-	-	-	
Tschingelgrat	Ts	-	-	-		1,1	1,1	20	L.Jur. - Valanginian	-	-	-	
Vättis	Va	-	-	-		1,1	1,1	20	L.Jur. - Valanginian	-	-	-	
Wanneli	Wa	-	-	-		1,1	1,1	20	L.Jur.	-	-	-	
INFRAHELVETIC NAPPES (Morcles and Doldenhorn)													
Ferdenrothorn	Fe	1,1	1,1-**1,25**	70	Triassic - E.Cret.	1,03	1,03	10	Triassic - m.E.Jur.	1,07	**1,1**	20	m.E.Jur. - Oxfordien
						1,04	**1,1**	0	(2 solutions)	**1,05**	1,0	20	L.Jur.
Mont Joly	Mjo	1,15	**1,2**	60	L.Triassic - E.Cret.	1,05	1,05-**1,1**	10	L.Triassic - l.E.Jur.	1,1	1,1	10	l.E.Jur. - E.Cret.
Morcles	MoI	1,2	1,2-**1,3**	50	Triassic - E.Cret.	1,07	1,07-**1,1**	10	L.Triassic - l.E.Jur.	1,15	**1,2**	10	l.E.Jur. - E.Cret.
Torrenthorn	Th	1,15	**1,2**	60	Triassic - E.Cret.	1,06	**1,15**	0	Triassic - m.E.Jur.	1,15	**1,25**	20	m.E.Jur. - Oxfordian
						1,06	**1,1**	10	(2 solutions)	**1,05**	1,0	15	L.Jur.
HELVETIC *sensu stricto*													
Aermighorn	Ae	1,1	**?**	50	L.Triassic - E.Cret.	**1,07**	1,0-1,07	40	L.Triassic - M.Jur.	**1,05**	1,0-1,1	30	L.Jur. - E.Cret.
Alvier	Av	1,2	**?**	>70	Triassic - E.Cret.	**1,1**	1,05-1,1	40	Triassic - L.Jur.	**1,1**	1,05	10	Cret.
Bundstock	Bs	1,03	**?**		Sinemur. - E.Cret.	1,05	1,05	20	L.Jur.	-	-	-	
Lenk	Len	1,13	**1,35**	40	Sinemur. - Cret.	**1,08**	1,0	40	Sinemur. - Valang.		??		E.Cret.
Lüsis	Lu	**1,1**	1,0	70	Sinemur. - E.Cret.	1,07	1,07-**1,1**	20	Sinemur. - M.Jur.	**1,05**	1,0-1,05	20	L.Jur. - E.Cret.
Mürtschen	Mu	1,1	**?**		L.Jur.	-	-	-		-	-	-	
Prabé	Pr	1,13	1,13-**1,35**	60	L.Triassic - E.Cret.	1,1	1,1	40	L.Triassic - L.Jur.	1,05	1,05-**1,1**	30	L.Jur. - E.Cret.
Raron North	Rn	1,06	**?**		Triassic - E.Cret.	1,05	**1,15**	10	Triassic - E.Jur.	1,06	**1,15**	0	M.Jur.
Raron South	Rs	1,1	**1,25**	40	Triassic - E.Cret.	1,06	**1,1**	10	Triassic - m.E.Jur.	1,06	**1,1**	10	l.E.Jur. - E.Cret.
Rawil	Ra	1,13	**1,35?**	50	L.Triassic - E.Cret.	1,1	1,1	40	L.Triassic - L.Jur.	1,05	1,05-**1,1**	10	L.Jur. - E.Cret.

The 2^{nd} order phases are variable, even for very close sections. For example, a time-equivalent event (Triassic to Early and Middle Jurassic) suggests crustal extension for Humilly (Fig. 9B) and subcrustal extension for Faucigny. As for the Jura, the subsidence-driving mechanisms in the Plateau are non-uniform, especially for the 2^{nd} order events.

5.4 Aiguilles Rouges and northern Aar massifs (Fig. 9C and Table 4)

The 1^{st} order phase of the Aiguilles Rouges profiles cannot be modelled (no plateau or very moderate tectonic subsidence). At the northern border of the Aar massif, only one short but high-amplitude subsidence event occurring during the Late Jurassic is well defined. Some oscillations being already noted during Triassic and Middle Jurassic times, this phase is considered as a 2^{nd} order event. The absence, in some sections, of a clear plateau during the Early Cretaceous constitutes a difficulty for the application of a model. However, for both the Aiguilles Rouges and Aar massifs, subsidence is adequately modelled by uniform extension (maximum of 10%, Table 4 and Fig. 9C). This zone differs from the Jura and Plateau areas by its homogeneous character.

5.5 Infrahelvetic nappes (Morcles and Doldenhorn, Fig. 9D and Table 4)

The long term Mesozoic tectonic subsidence is here best described by subcrustal stretching (Fig. 9D). However, the 50 to 70 M.y. rifting period appears unrealistic for this very northern location, with respect to the zone of active stretching (discussion in section 6).

The 2^{nd} order subsidence phases are well defined and, as a general rule, can be modelled by subcrustal stretching. The other two mechanisms are little represented (Table 4). Extension factors for the Triassic to Early Jurassic phase are very similar over the whole area. A Late Jurassic event is well documented in the Doldenhorn nappe only; unlike the northern Aar massif, it can be explained here by a crustal stretching model. Decoupling between the lithospheric layers is insufficient to generate uplift before initial fault-controlled subsidence (for parameters given in Table 3; see also Fig. 3 in Royden & Keen 1980).

5.6 Helvetic realm sensu stricto (Fig. 9E–F and Table 4)

Apart from indicating even more stretching in the lithospheric mantle, the profiles from the Raron syncline are very similar to the Morcles-Doldenhorn group, for long and short term subsidence (Fig. 9E).

The 1^{st} order subsidence of the other sections (Wildhorn and South-Helvetic area) is difficult to work out as it shows variable rifting periods, non-unique solutions and poor correlation between reconstructed subsidence and any theoretical curve. However, a subcrustal extension would again be appropriate, except for Lüsis where stretching seems confined to the curst (Table 4).

The 2^{nd} order phases fall into the crustal and uniform extension models. The stretching factors are quite uniform for all events. Slight indication towards subcrustal extension is provided by some sections. By its occasionally convex-upward shape, the Early Cretaceous major event cannot be properly modelled.

6. Conclusions and discussion

The conclusions drawn here are based on 5 profiles for the Jura, 5 for the Plateau, and 47 for the Helvetic realm *s.l.* The results obtained for the first two domains must be taken as preliminary. The limitations of the method applied to inverted basins are also reminded.

1) The two main superimposed tectonic subsidence phases (1st order or long term Mesozoic subsidence with a duration from 100 to 150 M.y. and 2nd order shorter phases [50–60 M.y.]) have been compared to three models of lithospheric extension: uniform, crustal and subcrustal stretching (see section 4).
2) The 1st order tectonic subsidence is often difficult to model. Despite this restriction, a trend towards subcrustal extension would be indicated for the Jura, Swiss Plateau and Helvetic realm (Table 5). Although less frequently encountered, the two other models are also suggested, and no overall subsidence-driving mechanism can be proposed for the entire study area. The stretching amounts range from 3 to 20% in the crust, and from 0 to 35% in the subcrustal lithosphere.
3) The 2nd order tectonic subsidence phases are better defined. A correspondence with one of the models is found in almost all situations. Extension in the crust ranges from 3 to 15%, and from 0 to 25% in the lithospheric mantle. As already noted for the tectonic subsidence, each paleogeographic realm is heterogeneous for itself, with two or three different suggested subsidence mechanisms (Table 5). By contrast, each sub-zone of the Helvetic realm *s.l.* is relatively homogeneous: uniform stretching in the northernmost part (Aiguilles Rouges and Aar massifs), subcrustal extension in the Morcles-Doldenhorn and Raron syncline domains and crustal to uniform extension in the Wildhorn and South-Helvetic regions. The

Table 5: Summary of the subsidence-driving mechanisms for each domain studied. Less frequently observed extension modes are indicated in brackets.

1st order	**Crustal stretching**	**Uniform stretching**	**Subcrustal stretching**
Jura	■	■	■
Plateau	-	-	■
Helvetic *s.l.*	(■)	?	■
- Aig. Rouges - north. Aar	?	?	?
- Morcles - Doldenhorn	-	-	■
- Helvetic *s.s.*	(■)	-	■
2nd order			
Jura	■	■	-
Plateau	■	■	■
Helvetic *s.l.*	■	■	■
- Aig. Rouges (-north. Aar)	-	■	-
- Morcles - Doldenhorn	(■)	(■)	■
- Raron syncline	-	-	■
- Wildhorn and South. Helv.	■	■	-

Aiguilles Rouges and northern Aar massifs constitute a little extended area between the Plateau and Helvetic zones where stretching is more pronounced.

4) The shape of the tectonic subsidence phases up to the end of the Jurassic is usually concave-upward, indicating the decay of a thermo-mechanical perturbation. The models tested are able to generate such subsidence cycles. However, they cannot predict the convex-upward subsidence frequently observed for the Early Cretaceous event of the South-Helvetic domain. Convex-upward forms can be related to flexure loading (e.g. Vail et al. 1991). The observed Early Cretaceous phase may thus be the consequence of the inception of compressional movements in more southern domains (e.g. Fig. 41 in Trümpy 1980); this phase would then no longer fall into the extensional system of the Triassic and Jurassic (see also Wildi et al. 1989).

From a theoretical point of view, the extensional phase lasts from the first tensional events (initiation of fault-controlled subsidence) to the formation of oceanic crust (onset of thermal relaxation). This time interval is thus fairly well constrained. For the Ligurian Tethys as a whole, a value of about 70 M.y. is proposed by Boillot et al. (1984, Late Triassic to Callovian-Oxfordian). The rifting period in a precise location is however restricted to a shorter time interval between the two extreme ages documented across the entire margin. For instance, a main rifting period of about 30 M.y. (Norian to early Toarcian) is adopted by Bertotti (1991) for the Lombardian basin (western Southern Alps). A similar duration of 35 M.y. is proposed by Stampfli & Marthaler (1990) for the Briançonnais.

Much variable rifting periods (Δt) are deduced from the models (Table 4) and values of 30 to 125 M.y. (mean of 60 M.y.) are needed to reproduce the complete Mesozoic 1st order subsidence. These durations are in agreement with the extensional period over the whole Ligurian Tethys (about 70 M.y.) but in contradiction with its shorter regional expression as mentioned above (about 30 M.y.). This argument, as well as the difficulties encountered in modelling the 1st order subsidence tend to invalidate the "one-rifting hypothesis": the Mesozoic tectonic subsidence is interpreted as the product of several successive modifications of the thermo-mechanical structure of the lithosphere between the Triassic and the Cretaceous ("re-rifting hypothesis"). On the other hand, the systematic use of a 30 M.y. rifting period for the 2nd order phases does not allow a plausible model to be found for many situations and variable rifting values have also to be applied (0 to 50 M.y.). However, this may here be the expression of regional and local lithospheric heterogeneities in a broader extensional system (see below).

The non-uniform subsidence patterns and driving mechanisms in the Jura-Plateau area contrast with the homogeneous character of the Helvetic sub-domains. This marked difference may express the major influence of late Variscan structures on the Mesozoic record in the Jura and Plateau, whereas basin development in the Helvetic realm is mainly controlled by extension on the North-Tethyan margin (see also Wildi et al. 1989). For the Jura and Plateau sections, tectonic subsidence may be seen as an indirect consequence of extension, which reactivated ancient structures. The ultimate control on subsidence is given by the type and orientation of past discontinuities. For the Helvetic realm however, stronger extension mechanisms exceeded the influence of the Variscan inheritance. Subsidence was the direct consequence of thinning processes in the lithosphere.

Extensional tectonics as suggested by the models can constitute the proper driving mechanism for the Triassic to Middle Jurassic subsidence phases. The Late Jurassic subsidence however, documented mainly in the external Aar massif, is difficult to explain as a product of stretching, because the main extension probably stopped at the end of the Middle Jurassic when oceanic crust was formed. The Late Jurassic subsidence is regarded as a consequence of differential stresses in the "foundering margin" (overall thermal relaxation). Such movements are also influenced by the structures inherited from the Triassic to Middle Jurassic phases, well documented in neighboring regions.

Some other paleogeographic elements can be deduced from this study:

- Early Jurassic sediments are partly missing on the Aiguilles Rouges and Aar massifs ("Alemannic Land", Trümpy 1949). The formation of this structural high is contemporaneous with subcrustal extension in the Morcles-Doldenhorn area. The "Alemannic Land" can thus be seen as a thermal bulge due to high lateral heat transfer from the area of active extension;
- as predicted by the subcrustal extension model, subsidence may have occurred in the Morcles-Doldenhorn and Raron areas without major attenuation of the crust. It is thus not surprising that paleofault activity was not recorded in the stratigraphy of this region (Loup 1992a);
- in contrast, paleofault activity should be better expressed in the Wildhorn domain, as suggested by the crustal extension model (high attenuation of the crust; e.g. Günzler-Seiffert 1941);
- such contrasting behaviors are possibly linked by oblique detachments through the lithosphere (simple shear model, e.g. Wernicke 1985, Gibbs 1987; see also Loup 1992b). This extensional geometry has the advantage of solving the space problem inherent in the subcrustal stretching model.

The final tectonic subsidence amplitudes, subsidence rates and stretching factors reconstructed for the study area are very low in comparison with the typical values observed on classical passive continental margins (see for example Watts & Ryan 1976, Watts & Steckler 1981, Steckler & Watts 1982, Sawyer et al. 1982, Swift et al. 1987; see also Funk 1985). An intracontinental character (sag basins on the stable European plate) or a very landward position of the Jura, Swiss Plateau and Helvetic realm with respect to a southerly located hinge zone is thus indicated by subsidence analysis and modelling. The studied domains are also interpreted by Stampfli & Marthaler (1990) as elements of a complex rim basin extending from the Jura to the external Briançonnais.

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